**AFRL-OSR-VA-TR-2014-0064**

# (DARPA) TOPOLOGICAL QUANTUM ENTANGLEMENT

**SANKAR DAS SARMA**

**UNIVERSITY OF MARYLAND COLLEGE PARK**

**02/19/2014**
**Final Report**



**AIR FORCE RESEARCH LABORATORY**
**AF OFFICE OF SCIENTIFIC RESEARCH (AFOSR)/RSE**
**ARLINGTON, VIRGINIA 22203**
**AIR FORCE MATERIEL COMMAND**

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
02-19-2014

**2. REPORT TYPE**
Final Performance Report

**3. DATES COVERED** *(From - To)*
Dec. 1, 2008 - Nov. 30, 2013

**4. TITLE AND SUBTITLE**
(DARPA) TOPOLOGICAL QUANTUM ENTANGLEMENT

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
FA9550-09-1-0037

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Das Sarma, Sankar (PI)
Freedman, Michael (co-PI)
Galitski, Victor (co-PI)
Nayak, Chetan (co-PI)
Shtengel, Kirill (co-PI)

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
University of Maryland, Department of Physics, College Park, MD 20742-4111
Microsoft Station Q, UCSB, Santa Barbara, CA 93106-6105
University of California-Riverside, Department of Physics and Astronomy, Riverside, CA 92521

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
AF Office of Scientific Research
875 N. Randolph Street, Room 3112
Arlington, VA 22203

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
Distribution A -- Approved for Public Release

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

**15. SUBJECT TERMS**

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | UU | | Sankar Das Sarma |
| | | | | | **19b. TELEPHONE NUMBER** *(include area code)* 301-405-6145 |

**Final Performance Report**

**To:** technicalreports@afosr.af.mil
**Subject:** Annual Performance Report to Dr. Tatjana Curcic

**Contract/Grant Title:** (DARPA) TOPOLOGICAL QUANTUM ENTANGLEMENT
**Contract/Grant #:** FA9550-09-1-0037
**Reporting Period:** Dec. 1, 2008 to Nov. 30, 2013

**Final accomplishments:**
All the work proposed by us in our proposal has been accomplished and surpassed. Our DARPA QuEST supported work has led to 78 publications.

Shtengel's Important results:

***Experimental signatures of non-Abelian anyons***

*(i)* ν=5/2 *state FQHE*

Perhaps the most striking signature of non-Abelian statistics of anyons in the ν=5/2 fractional quantum Hall (FQH) state – the most likely FQH state to host such quasiparticles – is the so-called even-odd effect predicted for quantum interference experiments [*A. Stern, B. Halperin,* Phys. Rev. Lett. 96, 016802 (2006), *P. Bonderson, A. Kitaev and K. Shtengel,* Phys. Rev. Lett. 96, 016803 (2006)]. Whether or not the interference occurs depends on the parity of Ising anyons inside the interference loop. While some indications of this effect were in fact seen in a series of experiments on a two point contact FQH device at filling ν=5/2 and reported in [*R. L. Willett, L. N. Pfeiffer and K. W. West,* PNAS 106, 8853 (2009) and Phys. Rev. B 82,205301 (2010)], the experimental data had been too noisy to convincingly rule out other possibilities and quiet the critics. In order to better understand what had been seen experimentally, we analyzed several plausible scenarios that could lead to observed oscillations. Such scenarios essentially could correspond to one of the two possibilities: the device may function as a Fabry-Pérot interferometer, in which case the oscillations result from the interference of (fractionalized) edge quasiparticles taking two possible paths, or the oscillations may result from the Coulomb blockade-type physics. By comparing different existing models of the ν=5/2 state (which are not all non-Abelian!), we have analyzed several possible explanations of two phenomena reported by Willett and coworkers, namely halving of the period of the observed resistance oscillations with rising temperature and alternation between the same two observed periods at low temperatures as the area of the interference loop is varied with a side gate. We have concluded that the most likely explanation is that the observed alternation is due to switching between even and odd numbers of charge $e/4$ quasiparticles enclosed within the loop as a function of side gate voltage, which is a clear signature of a non-Abelian nature of the state. We have also suggested further experiments which could help rule out some possible scenarios. Some of these suggestions are being implemented by the experimentalists. Our analysis [*W. Bishara, P. Bonderson, C. Nayak, K. Shtengel, J. K. Slingerland* , Phys. Rev. B 80, 155303 (2009)] was published as "Editor's suggestion" and was selected for a Viewpoint commentary in Physics [*J. E. Moore*, Physics 2, 82 (2009)].

As a closely related offshoot of the previous publication, we have also investigated in detail what are the potential experimental signatures of the Coulomb blockade effects in such systems. Our conclusion, reported in [*P. Bonderson, C. Nayak, K. Shtengel*, Phys. Rev. B 81, 165308 (2010), Editor's suggestion], is that, unlike quasiparticle interferometers, the Coulomb blockaded devices are much less likely to provide us with definitive signatures of non-Abelian nature of excitations.

Concerning the interpretation of the experiments by Willett and coworkers, our analysis described above did not address one very important concern: the stability of the phase of the reported Aharonov–Bohm oscillations to the tunneling of neutral quasiparticles between the bulk and the edge. Naïve estimates can lead one to a conclusion that such tunneling events would scramble the phase, completely washing out the oscillations. This, in turn, makes one wonder why any oscillation signal has been seen at all. Addressing this question in [*D. J. Clarke and K. Shtengel*, New J. Phys. 13, 055005 (2011)], we offered two possible mechanisms for stabilizing the phase of Aharonov–Bohm oscillations: a quantum Zeno effect (a stabilization of a quantum state that is being continuously measured) and a polarization of a qubit due to its interaction with the edge. We have argued that the latter mechanism provides a plausible explanation for the observations made by Willett and coworkers.

Finally, in [*R. L Willett, C. Nayak, K. Shtengel, L. N. Pfeiffer, K. W. West*, Phys. Rev. Lett. 111, 186401 (2013)] we revisited the earlier interferometeric setup, this time focusing on the periodicity of Aharonov–Bohm oscillations as a function of *both* the side-gate voltage and the applied magnetic field. (Previous studies focused on the oscillations driven by side-gate voltage alone.) We predicted a qualitative difference in the resistance oscillations with magnetic field of the $\nu$=5/2 quantum Hall state, confined to an interferometer, depending on whether this state is Abelian or non-Abelian. Specifically, an Abelian state such as the (3,3,1) state would show oscillations with the same period as seen at an integer quantum Hall state. However, in an Ising-type non-Abelian state there would be a rapid oscillation associated with the "even-odd effect" and a slower one associated with the accumulated Abelian phase due to both the Aharonov-Bohm effect and the Abelian part of the quasiparticle braiding statistics. The measurements we suggested have been performed by R. Willett and appear to be consistent with the latter scenario, adding confidence to the expectation that the observed $\nu$=5/2 FQH state is indeed non-Abelian.

*(ii) Other candidate systems*

Several other systems have been proposed to host non-Abelian anyons of the Ising type – i.e. of the type expected to be found in the $\nu$=5/2 state. While it has been understood for some time that such anyons – Majorana zero modes – can exist in vortex cores in 2D chiral *p*-wave superconductors (SC), further research in that direction was hampered by the lack of such readily available superconductors. However, following the prediction and subsequent discovery of 3D topological insulators, it was found that essentially the same physics can be realized on a surface of such an insulator in proximity to an *s*-wave superconductor. Another modification of this idea suggested by the Maryland group (as a part of this funded effort) is replacing a topological insulator by a "sandwich" structure made of a SC with strong spin-orbit coupling and a magnetic insulator. A natural question then arises: how do we detect non-Abelian anyons in such systems. In order to address this question we focused on developing experimental probes for Majorana modes in such topological superconductors (intrinsic or artificial). Most predicted experimental signatures of Majorana zero modes such as a zero-bias tunneling anomaly or the fractional Josephson effect are only very indirect probes of their non-Abelian nature. In [*C.-Y. Hou, K. Shtengel, G. Refael, P. M. Goldbart*, New J. Phys. 14, 105005 (2012)] we proposed an experiment for detecting the excess entropy of Majorana modes which accompany vortices in topological SC. Our proposal is based on the magneto-thermoelectric effect which manifests itself through the temperature difference between two opposite edges of a topological superconductor that results from the motion of vortices hosting Majorana. We have proposed a specific setup which utilizes a wide Josephson junction. The use of a wide junction makes the predicted Ettingshausen effect lie within an experimentally accessible range of parameters. Our work not only offers a novel route to detection of Majorana states in topological superconductors, it aims directly at probing the intrinsic entropy associated with Majorana zero-energy modes – a necessary feature for their non-Abelian statistics – hence offering a glimpse into their unconventional nature.

Finally, in order to develop a reliable technique for measuring the electron temperature at an edge of a topological superconductor (an important experimental parameter for any potential practical applications of chiral edge states in these systems), in [*C.-Y. Hou, K. Shtengel, G. Refael*, Phys. Rev. B 88 075304 (2013)] we investigated the thermoelectric effect between a conducting lead and a Majorana edge state. We confirmed that a non-vanishing thermopower can generically exist in this setting (which was not obvious, owing to the particle-hole symmetry of the superconducting edge state) and verified the Mott formula, which is instrumental to inferring the temperature of the Majorana edge state from measurements of the differential conductance and the voltage induced by the temperature difference between the conducting lead and the edge state.

***Quantum circuitry for topological quantum computation***

One of the crucial issues being faced by topological quantum computation is that non-Abelian anyons of the Ising kind appear to be most likely realized in a variety of physical systems, while the existence of other non-Abelian anyons in the experimentally feasible settings appears more doubtful at this point. Unfortunately, braiding and measuring Ising anyons alone cannot produce a computationally universal gate set. Hence, a vital open problem that must be addressed is how to practically achieve universal quantum computation using Ising anyons. We first focused our attention on the $\nu$=5/2 FQH setting and put forward a practical proposal in which a topological qubit is enclosed in a “sack” formed by a quantum Hall liquid with the quantum point contact. This geometry allows for the interference of two paths the quasiprticles may take around the qubit: travelling around the edge of the sack and tunnelling through the QPC. We have shown that by controlling the tunnelling transparency of the QPC one can implement arbitrary single qubit phase gates for Ising anyons [*P. Bonderson, D. J. Clarke, C. Nayak and K. Shtengel*, Phys. Rev. Lett. 104, 180505 (2010)]. Adding such gates (in particular the $\pi$/8-phase gate) to the Ising gate set that can be obtained by brading/measurement techniques makes it computationally universal.

Building on this idea, we also came up with a conceptual design and subsequent analysis of the phase gate in systems with topological superconductivity and identified both advantages and shortcomings in comparison to the FQH based systems [*D. J. Clarke and K. Shtengel*, Phys. Rev. B 82, 180519 (2010), Editor's Suggestion]. The key difference between these two cases is that unlike the $\nu$=5/2 quantum Hall setting, in the case of topological superconductors the non-Abelian particles are electrically neutral. This, in turn, leads to both new challenges and some benefits. The following findings are of particular interest: (i) The error rate for systems with neutral Ising anyons (e.g. topological superconductors) has been found to be inherently lower than that for systems in which the anyons carry charge (e.g. quantum Hall systems); (ii) We proposed to use interference between Josephson vortices to effect the phase gate, this novel idea has been sicnce picked up by others for general inferometry purposes. We also proposed a practical way of controlling the tunnelling of non-Abelian quasiparticles in systems based on topological superconductivity where standard techniques based on electrostatic gating would not work.

***Engineering novel systems with non-Abelian anyons***

Taking a cue from the conceptual designs of so-called "Majorana wires", we have introduced a device fabricated from conventional fractional quantum Hall states, *s*-wave superconductors and insulators with strong spin–orbit coupling[*D. J. Clarke, J. Alicea, K. Shtenge*l, Nat. Commun. 4, 1348 (2013)]. Similarly to a Majorana wire, the ends of our "quantum wire" would bind "parafermions", exotic non-Abelian anyons which can be viewed as fractionalized Majorana zero modes. These modes can be experimentally identified (and distinguished from Majoranas) using tunnelling zero-bias anomaly (combined with noise measurements) and/or Josephson measurements. We have also provided a practical recipe for braiding parafermions and derived their non-Abelian statistics. Aside from the interesting new physics, these anyons present new possibilities for quantum information processing – they allow for braiding-only entangling quantum gates which are not possible for Ising anyons (e.g. unpaired Majorana modes).

Build upon this construction, we have found that the aforementioned setup can be much simplified in the case of spin-unpolarized FQH states such as 2/3 or 2/5. Moreover, the unusual physics associated with zero modes in these systems allows us to design such exotic circuit elements as current mirrors and DC transformers.

Another extremely exciting possibility, which builds on the above occurs when a network of judiciously patterned "trenches" -- hosting the aforementioned parafermionic zero modes -- is created in such a way that these zero modes interact with one another. We have found that the system can be driven into a stable 2D "Fibonacci phase" [*R.S.K. Mong et al*, arXiv:1307.4403, to appear in Phys. Rev. X]. The non-Abelian particles in this phase are *Fibonacci anyons* whose remarkable feature is their computational universality. The ability to braid Fibonacci anyons and to measure them is sufficient to perform any desired quantum computation in a completely protected manner.

Nayak's Important results:

"Numerical Calculation of the Neutral Fermion Gap at ν=5/2", Parsa Bonderson, Adrian E. Feiguin, Chetan Nayak, Phys. Rev. Lett. 106, 186802 (2011).

The 5/2 quantum Hall state is often viewed as a quantum Hall analogue of a chiral p-wave superconductor, and this analogy lies at the heart of research that seeks to use these states for topological quantum information. However, this analogy begs the previously unanswered question: what is the superconducting gap in the 5/2 quantum Hall state? In this paper, we gave the first calculation of this gap, which is relevant to the error rate for topological qubits in the 5/2 state.

"Projective Ribbon Permutation Statistics: a Remnant of non-Abelian Braiding in Higher Dimensions", Michael Freedman, Matthew B. Hastings, Chetan Nayak, Xiao-Liang Qi, Kevin Walker, Zhenghan Wang, Phys. Rev. B 83, 115132 (2011).

"Weakly-Coupled non-Abelian Anyons in Three Dimensions", Michael Freedman, Matthew B. Hastings, Chetan Nayak, Xiao-Liang Qi, Phys. Rev. B 84, 245119 (2011).

In these papers, we analyzed the possibility of Ising-type non-Abelian anyons in *three dimensions*, following a suggestion of Jeffrey Teo and Charlie Kane. We showed that certain types of solitons in three-dimensional ordered media could support an analogue of non-Abelian statistics due to their extended nature whose topology is governed by the ribbon permutation group.

"Majorana Zero Modes in 1D Quantum Wires Without Long-Ranged Superconducting Order", Lukasz Fidkowski, Roman M. Lutchyn, Chetan Nayak, Matthew P.A. Fisher, Phys. Rev. B 84, 195436 (2011).

In this paper, we showed that Majorana zero modes can occur even in systems that do not have long-ranged superconducting order. Algebraically-decaying order is sufficient, which means that a bulk 3D superconductor is not necessary for the observation of Majorana zero modes in nanowires. Coating the nanowire with a film (which is possible with MBE growth) is expected to lead to such order, and this result encourages exploration in this direction.

"Magnetic and Superconducting Ordering at $LaAlO_3/SrTiO_3$ Interfaces", Lukasz Fidkowski, Hong-Chen Jiang, Roman M. Lutchyn, Chetan Nayak, Phys. Rev. B 87, 014436 (2013).

In this paper, we constructed a model of the conducting state at the LAO/STO interface that explains both magnetic and superconducting order. This model predicts that Majorana zero modes can occur in nanowires "drawn" with an atomic force microscope tip.

"Majorana Zero Modes in Semiconductor Nanowires in Contact with Higher-$T_c$ Superconductors", Younghyun Kim, Jennifer Cano, Chetan Nayak, Phys. Rev. B 86, 235429 (2012).

In this paper, we showed that cuprate and, especially, pnictide superconductors can help stabilize Majorana zero modes in semiconductor nanowires at relatively high temperatures. We showed that the Fermi surface mismatches and the sign change of the order parameter can be overcome by, for instance, using a step-edge interface.

"Metaplectic Anyons, Majorana Zero Modes, and their Computational Power", Matthew B. Hastings, Chetan Nayak, Zhenghan Wang, Phys. Rev. B 87, 165421 (2013).

In this paper, we analyzed a model of anyons – metaplectic anyons – that is the underlying anyon model behind the "parafermion" zero modes discussed by Clarke et al. (see above), Linder et al., and Barkeshli and Qi. Although these anyons are not universal for quantum computation, their braiding cannot be efficiently simulate classically. This a rare example of a topological phase that is not universal for quantum computation through braiding but nevertheless has #P-hard link invariants.

"The Effect of Landau Level-Mixing on the Effective Interaction between Electrons in the fractional quantum Hall regime", Waheb Bishara, Chetan Nayak, Phys. Rev. B 80, 121302 (2009).

"More Realistic Hamiltonians for the Fractional Quantum Hall Regime in GaAs and Graphene", Michael R. Peterson, Chetan Nayak, Phys. Rev. B 87, 245129 (2013).

These papers give the first controlled calculation of effective Hamiltonians for the fractional quantum Hall regime that incorporate the effects of Landau-level mixing and sub-band mixing. This Hamiltonian is relevant to the competition between the Pfaffian and anti-Pfaffian states at 5/2 as well and to states in the N=1 Landau level more generally.

“Bulk-Edge Correspondence in 2+1-Dimensional Abelian Topological Phases”, Jennifer Cano, Meng Cheng, Michael Mulligan, Chetan Nayak, Eugeniu Plamadeala, Jon Yard, arXiv:1310.5708.

This paper gives the first precise characterization of the relationship between bulk and edge in the fractional quantum Hall effect. We showed that the correspondence is one-to-many: while edge states can be classified by integral lattices, bulk states are classified by genera of lattices. This has implications for efforts to identify quantum Hall states through exponents obtained from transport through quantum point contacts.

**Archival publications during reporting period:**


1. Spin Polarization of the ν=5/2 Quantum Hall State (A.E. Feiguin, E. Rezayi, K. Yang, C. Nayak, and S. Das Sarma), Phys. Rev. B **79**, 115322 (2009). arXiv:0804.4502

2. Interferometric Signature of Non-Abelian Anyons (W. Bishara, P. Bonderson, C. Nayak, K. Shtengel, and J.K. Slingerland), Phys. Rev. B **80**, 155303 (2009). arXiv:0903.3108

3. Splitting of Majorana-Fermion Modes Due to Intervortex Tunneling in a $p_x+ip_y$ Superconductor (M. Cheng, R.M. Lutchyn, V.M. Galitski, and S. Das Sarma), Phys. Rev. Lett. **103**, 107001 (2009). arXiv:0905.0035

4. Probing Kitaev Models on Small Lattices (H.D. Chen, B. Wang, and S. Das Sarma), Phys. Rev. B **81**, 235131 (2010). arXiv:0906.0017

5. The Enigma of the ν=0 Quantum Hall Effect in Graphene (S. Das Sarma and K. Yang), Solid State Commun. (Fast Track) **149**, issues 37-38, 1502-1506 (2009). arXiv:0906.2209

6. Generic New Platform for Topological Quantum Computation Using Semiconductor Heterostructures (J.D. Sau, R.M. Lutchyn, S. Tewari, and S. Das Sarma), Phys. Rev. Lett. **104**, 040502 (2010). arXiv:0907.2239

7. Stable Topological Superconductivity in a Family of Two-Dimensional Fermion Models (M. Cheng, K. Sun, V.M. Galitski, and S. Das Sarma), Phys. Rev. B **81**, 024504 (2010). arXiv:0908.2805

8. Coulomb Blockade Doppelgangers in Quantum Hall States (P. Bonderson, C. Nayak, and K. Shtengel), Phys. Rev. B **81**, 165308 (2010). arXiv:0909.1056

9. Half-Filled 2D Bilayers in a Strong Magnetic Field: Revisiting the ν=1/2 Fractional Quantum Hall Effect (S. Das Sarma and M.R. Peterson) arXiv:0910.4385

10. A Theorem for the Existence of Majorana Fermion Modes in Spin-Orbit-Coupled Semiconductors (S. Tewari, J.D. Sau, and S. Das Sarma), Annals of Physics **325**, 219 (2010). arXiv:0910.4763

11. Implementing Arbitrary Phase Gates with Ising Anyons (P. Bonderson, D.J. Clarke, C. Nayak, and K. Shtengel), Phys. Rev. Lett. **104**, 180505 (2010). arXiv:0911.2691

12. Robustness of Majorana Fermions in Proximity-Induced Superconductors (J.D. Sau, R.M. Lutchyn, S. Tewari, and S. Das Sarma), Phys. Rev. B **82**, 094522 (2010). arXiv:0912.4508

13. Proximity Effect at the Superconductor-Topological Insulator Interface (T.D. Stanescu, J.D. Sau, R.M. Lutchyn, and S. Das Sarma), Phys. Rev. B (Rapid Commun.) **81**, 241310(R) (2010). arXiv:1002.0842

14. Majorana Fermions and a Topological Phase Transition in Semiconductor-Superconductor Heterostructures (R.M. Lutchyn, J.D. Sau, and S. Das Sarma), Phys. Rev. Lett. **105**, 077001 (2010). arXiv:1002.4033

15. Quantum Hall Phase Diagram of Half-Filled Bilayers in the Lowest and the Second Orbital Landau Levels: Abelian versus Non-Abelian Incompressible Fractional Quantum Hall States (M.R. Peterson and S. Das Sarma), Phys. Rev. B **81**, 165304 (2010). arXiv:1002.4359

16. Antiferromagnetic Spinor Condensates are Quantum Rotors (R. Barnett, J.D. Sau, and S. Das Sarma), Phys. Rev. A (Rapid Commun.) **82**, 031602(R) (2010). arXiv:1003.2634

17. Probing Non-Abelian Statistics with Majorana Fermion Interferometry in Spin-Orbit-Coupled Semiconductors (J.D. Sau, S. Tewari, and S. Das Sarma), Phys. Rev. B **84**, 085109 (2011). arXiv:1004.4702

18. Tunneling of Anyonic Majorana Excitations in Topological Superconductors (M. Cheng, R.M. Lutchyn, V.M. Galitski, and S. Das Sarma), Phys. Rev. B **82**, 094504 (2010). arXiv:1006.0452

19. Non-Abelian Quantum Order in Spin-Orbit-Coupled Semiconductors: Search for Topological Majorana Particles in Solid State Systems (J.D. Sau, S. Tewari, R.M. Lutchyn, T.D. Stanescu, and S. Das Sarma), Phys. Rev. B **82**, 214509 (2010). arXiv:1006.2829

20. Non-Abelian Topological Order in Noncentrosymmetric Superconductors with Broken Time-Reversal Symmetry (P. Ghosh, J.D. Sau, S. Tewari, and S. Das Sarma), Phys. Rev. B **82**, 184525 (2010). arXiv:1006.3083

21. Universal Quantum Computation on a Semiconductor Quantum Wire Network (J.D. Sau, S. Tewari, and S. Das Sarma), Phys. Rev. A **82**, 052322 (2010). arXiv:1007.4204

22. Gutzwiller-Projected Wave Functions for the Pseudogap State of Underdoped High-Temperature Superconductors (R. Sensarma and V.M. Galitski), Phys. Rev. B (Rapid Commun.) **84**, 060503(R) (2011). arXiv:1007.5067

23. Search for Majorana Fermions in Multiband Semiconductor Nanowires (R.M. Lutchyn, T.D. Stanescu, and S. Das Sarma), Phys. Rev. Lett. **106**, 127001 (2011). arXiv:1008.0629

24. Numerical Calculation of the Neutral Fermion Gap at $\nu=5/2$ (P. Bonderson, A.E. Feiguin, and C. Nayak), Phys. Rev. Lett. **106**, 186802 (2011). arXiv:1008.4173

25. Plasma Analogy and Non-Abelian Statistics for Ising-Type Quantum Hall States (P. Bonderson, V. Gurarie, and C. Nayak), Phys. Rev. B **83**, 075303 (2011). arXiv:1008.5194

26. Improved Phase Gate Reliability in Systems with Neutral Ising Anyons (D.J. Clarke and K. Shtengel), Phys. Rev. B (Rapid Commun.) **82**, 180519(R) (2010). arXiv:1009.0302

27. Diamagnetic Susceptibility Obtained from the Six-Vertex Model and Its Implications for the High-Temperature Diamagnetic State of Cuprate Superconductors (J.D. Sau and S. Tewari), Phys. Rev. Lett. **107**, 177006 (2011). arXiv:1009.5926

28. Anisotropic Surface Transport in Topological Insulators in Proximity to a Helical Spin Density Wave (Q. Li, P. Ghosh, J.D. Sau, S. Tewari, and S. Das Sarma), Phys. Rev. B **83**, 085110 (2011). arXiv:1010.0683

29. Prediction of a Gapless Topological Haldane Liquid Phase in a One-Dimensional Cold Polar Molecular Lattice (J.P. Kestner, B. Wang, J.D. Sau, and S. Das Sarma), Phys. Rev. B **83**, 174409 (2011). arXiv:1011.2490

30. Topologically Non-Trivial Superconductivity in Spin-Orbit-Coupled Systems: Bulk Phases and Quantum Phase Transitions (S. Tewari, T.D. Stanescu, J.D. Sau, and S. Das Sarma), New J. Phys. **13**, 065004 (2011). Invited Review. arXiv:1012.0057

31. Chiral Rashba Spin Textures in Ultracold Fermi Gases (J.D. Sau, R. Sensarma, S. Powell, I.B. Spielman, and S. Das Sarma), Phys. Rev. B (Rapid Commun.) **83**, 140510(R) (2011). arXiv:1012.3170

32. Edge-Induced Qubit Polarization in Systems with Ising Anyons (D.J. Clarke and K. Shtengel), New J. Phys. **13**, 055005 (2011). arXiv:1102.2016

33. Avoidance of Majorana Resonances in Periodic Topological Superconductor-Nanowire Structures (J.D. Sau, C.H. Lin, H.Y. Hui, and S. Das Sarma), Phys. Rev. Lett. **108**, 067001 (2012). arXiv:1103.2770

34. Effective Field Theory of Fractional Quantized Hall Nematics (M. Mulligan, C. Nayak, and S. Kachru), Phys. Rev. B **84**, 195124 (2011). arXiv:1104.0256

35. SU(2) Slave Fermion Solution of the Kitaev Honeycomb Lattice Model (F.J. Burnell and C. Nayak), Phys. Rev. B **84**, 125125 (2011). arXiv:1104.5485

36. Entanglement Measures for Quasi-Two-Dimensional Fractional Quantum Hall States (J. Biddle, M.R. Peterson, and S. Das Sarma), Phys. Rev. B **84**, 125141 (2011). arXiv:1105.1385

37. Nonadiabatic Effects in the Braiding of Non-Abelian Anyons in Topological Superconductors (M. Cheng, V.M. Galitski, and S. Das Sarma), Phys. Rev. B **84**, 104529 (2011). arXiv:1106.2549

38. Majorana Zero Modes in One-Dimensional Quantum Wires Without Long-Ranged Superconducting Order (L. Fidkowski, R.M. Lutchyn, C. Nayak, and M.P.A. Fisher), Phys. Rev. B **84**, 195436 (2011). arXiv:1106.2598

39. Majorana Edge States in Interacting Two-Chain Ladders of Fermions (M. Cheng and H.H. Tu), Phys. Rev. B **84**, 094503 (2011). arXiv:1106.2614

40. Majorana Fermions in Semiconductor Nanowires (T. Stanescu, R.M. Lutchyn, and S. Das Sarma), Phys. Rev. B **84**, 144522 (2011). arXiv:1106.3078

41. Number Conserving Theory for Topologically Protected Degeneracy in One-Dimensional Fermions (J.D. Sau, B.I. Halperin, K. Flensburg, and S. Das Sarma), Phys. Rev. B **84**, 144509 (2011). arXiv:1106.4014

42. Probing a Topological Quantum Critical Point in Semiconductor-Superconductor Heterostructures (S. Tewari, J.D. Sau, V.W. Scarola, C. Zhang, and S. Das Sarma), Phys. Rev. B **85**, 155302 (2012). arXiv:1106.5506

43. Higgs Transitions of Spin Ice (S. Powell), Phys. Rev. B **84**, 094437 (2011). arXiv:1106.6046

44. Weakly-Coupled Non-Abelian Anyons in Three Dimensions (M. Freedman, M.B. Hastings, C. Nayak, and X.L. Qi), Phys. Rev. B **84**, 245119 (2011). arXiv:1107.2731

45. Momentum Relaxation in a Semiconductor Proximity-Coupled to a Disordered S-Wave Superconductor: Effect of Scattering on Topological Superconductivity (R.M. Lutchyn, T.D. Stanescu, and S. Das Sarma), Phys. Rev. B (Rapid Commun.) **85**, 140513(R) (2012). arXiv:1110.5643

46. Screening Properties and Phase Transitions in Unconventional Plasmas for Ising-Type Quantum Hall States (E.V. Herland, E. Babaev, P. Bonderson, V. Gurarie, C. Nayak, and A. Sudbo), Phys. Rev. B **85**, 024520 (2012). arXiv:1111.0135

47. Experimental and Materials Considerations for the Topological Superconducting State in Electron- and Hole-Doped Semiconductors: Searching for non-Abelian Majorana Modes in 1D Nanowires and 2D Heterostructures (J.D. Sau, S. Tewari, and S. Das Sarma), Phys. Rev. B **85**, 064512 (2012). arXiv:1111.2054

48. Realizing a Robust Practical Majorana Chain in a Quantum-Dot-Superconductor Linear Array (J.D. Sau and S. Das Sarma), Nature Commun. **3**, 964 (2012). arXiv:1111.6600

49. Topological Protection of Majorana Qubits (M. Cheng, R.M. Lutchyn, and S. Das Sarma), Phys. Rev. B **85**, 165124 (2012). arXiv:1112.3662

50. Josephson Current through a Superconductor/Semiconductor-Nanowire/Superconductor Junction: Effects of Strong Spin-Orbit Coupling and Zeeman Splitting (M. Cheng and R.M. Lutchyn), Phys. Rev. B **86**, 134522 (2012). arXiv:1201.1918

51. Quantum Phases of Disordered Flatband Lattice Fractional Quantum Hall Systems (S. Yang, K. Sun, and S. Das Sarma), Phys. Rev. B **85**, 205124 (2012). arXiv:1202.1526

52. Interplay of Disorder and Interaction in Majorana Quantum Wires (A.M. Lobos, R.M. Lutchyn, and S. Das Sarma), Phys. Rev. Lett. **109**, 146403 (2012). arXiv:1202.2837

53. Magnetic Phases in the One-Dimensional Kondo Chain on a Metallic Surface (A.M. Lobos, M.A. Cazalilla, and P. Chudzinski), Phys. Rev. B **86**, 035455 (2012). arXiv:1202.5545

54. Ettingshausen Effect Due to Majorana Modes (C.Y. Hou, K. Shtengel, G. Refael, and P.M. Goldbart), New J. Phys. **14**, 105005 (2012). arXiv:1203.5793

55. Topological Minigap in Quasi-One-Dimensional Spin-Orbit-Coupled Semiconductor Majorana Wires (S. Tewari, T.D. Stanescu, J.D. Sau, and S. Das Sarma), Phys. Rev. B **86**, 024504 (2012). arXiv:1204.3637

56. Exotic Non-Abelian Anyons from Conventional Fractional Quantum Hall States (D.J. Clarke, J. Alicia, and K. Shtengel), Nature Commun. **4**, 1348 (2013). arXiv:1204.5479

57. Andreev Bound States in a One-Dimensional Topological Superconductor (X.J. Liu), Phys. Rev. Lett. **109**, 106404 (2012). arXiv:1204.0570

58. Intrinsic Electron-Phonon Resistivity of $Bi_2Se_3$ in the Topological Regime (D. Kim, Q. Li, P. Syers, N.P. Butch, J. Paglione, S. Das Sarma, and M.S. Fuhrer), Phys. Rev. Lett. **109**, 166801 (2012). arXiv:1205.5554

59. Topological Flat Band Models with Arbitrary Chern Numbers (S. Yang, Z.C. Gu, K. Sun, and S. Das Sarma), Phys. Rev. B (<u>Rapid Commun.</u>) **86**, 241112(R) (2012). arXiv:1205.5792

60. To Close or Not to Close: The Fate of the Superconducting Gap Across the Topological Quantum Phase Transition in Majorana-Carrying Semiconductor Nanowires (T.D. Stanescu, S. Tewari, J.D. Sau, and S. Das Sarma), Phys. Rev. Lett. **109**, 266402 (2012). arXiv:1206.0013

61. Topological Superconductivity and Majorana Fermions in Hybrid Structures Involving Cuprate High-Tc Superconductors (S. Takei, B.M. Fregoso, V.M. Galitski, and S. Das Sarma), Phys. Rev. B **87**, 014504 (2013). arXiv:1206.3226

62. Magnetic and Superconducting Ordering in One-Dimensional Nanostructures at the $LaAlO_3/SrTiO_3$ Interface (L. Fidkowski, H.C. Jiang, R.N. Lutchyn, and C. Nayak), Phys. Rev. B **87**, 014436 (2013). arXiv:1206.6959

63. Manipulating Majorana Fermions in Quantum Nanowires with Broken Inversion Symmetry (X.J. Liu and A.M. Lobos), Phys. Rev. B (<u>Rapid Commun.</u>) **87**, 060504(R) (2013). arXiv:1206.7109

64. Majorana Zero Modes in Semiconductor Nanowires in Contact with Higher-$T_c$ Superconductors (Y. Kim, J. Cano, and C. Nayak), Phys. Rev. B **86**, 235429 (2012). arXiv:1208.3701

65. Manipulating Topological Edge Spins in One-Dimensional Optical Lattice (X.J. Liu, Z.X. Liu, and M. Cheng), Phys. Rev. Lett. **110**, 076401 (2013). arXiv:1209.2990

66. Metaplectic Anyons, Majorana Zero Modes, and their Computational Power (M.B. Hastings, C. Nayak, and Z. Wang), Phys. Rev. B **87**, 165421 (2013). arXiv:1210.5477

67. Splitting of the Zero-Bias Conductance Peak as Smoking Gun for the Existence of the Majorana Mode in a Superconductor-Semiconductor Nanowire (S. Das Sarma, J.D. Sau, and T.D. Stanescu), Phys. Rev. B (<u>Rapid Commun.</u>) **86**, 220506(R) (2012). arXiv:1211.0539

68. Soft Superconducting Gap in Semiconductor Majorana Nanowires (S. Takei, B.M. Fregoso, H.Y. Hui, A.M. Lobos, and S. Das Sarma), Phys. Rev. Lett. **110**, 186803 (2013). arXiv:1211.1029

69. Quasi-Topological Phases of Matter and Topological Protection (P. Bonderson and C. Nayak), Phys. Rev. B **87**, 195451 (2013). arXiv:1212.6395

70. Freezing of an Unconventional Two-Dimensional Plasma (E.V. Herland, E. Babaev, P. Bonderson, V. Gurarie, C. Nayak, L. Radzihovsky, and A. Sudbo), Phys. Rev. B **87**, 075117 (2013). arXiv:1301.3914

71. Superconducting Proximity Effect in Semiconductor Nanowires (T.D. Stanescu and S. Das Sarma), Phys. Rev. B (Rapid Commun.) **87**, 180504 (2013). arXiv:1303.1187

72. Proposed Chiral Texture of the Magnetic Moments of Unit-Cell Loop Currents in the Pseudogap Phase of Cuprate Superconductors (S.S. Pershoguba, K. Kechedzhi, and V.M. Yakovenko), Phys. Rev. Lett. **111**, 047005 (2013). arXiv:1303.2982

73. Variational Monte Carlo Study of Spin-Polarization Stability of Fractional Quantum Hall States Against Realistic Effects in Half-Filled Landau Levels (J. Biddle, M.R. Peterson, and S. Das Sarma), Phys. Rev. B **87**, 235134 (2013). arXiv:1304.1174

74. Universal Density Scaling of Disorder-Limited Low-Temperature Conductivity in High-Mobility Two-Dimensional Systems (S. Das Sarma and E.H. Hwang), Phys. Rev. B **88**, 035439 (2013). arXiv:1304.4668

75. Electrical Detection of Topological Phase Transitions in Disordered Majorana Nanowires (B.M. Fregoso, A.M. Lobos, and S. Das Sarma), Phys. Rev. B (Rapid Commun.) **88**, 180507(R) (2013). arXiv:1307.3505

76. Magnetic Field-Tuned Aharonov-Bohm Oscillations and Evidence for Non-Abelian Anyons at $\nu=5/2$ (R.L. Willett, C. Nayak, K. Shtengel, L.N. Pfeiffer, and K.W. West) arXiv:1301.2639

77. Thermopower and the Mott Formula for a Majorana Edge State (C.Y. Hou, K. Shtengel, and G. Refael), arXiv:1305.5292

78. Soft Superconducting Gap in Semiconductor-based Majorana Nanowires (T.D. Stanescu, R.M. Lutchyn, and S. Das Sarma) arXiv:1311.2075

**Changes in research objectives:** none

**Change in AFOSR program manager:** none

**Extensions granted or milestones slipped:** N/A

**Include any new discoveries, inventions, or patent disclosures during this reporting period:** N/A